

Projected Coherent Perfect Absorption at Exceptional Points via Nonlocal Elastodynamic Coupling

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In non-Hermitian physics, coherent perfect absorption at an exceptional point (CPA EP) emerges as a unique degenerate state that can manifest anomalously broadened absorption line shape implying strong robustness, which apparently contradicts the extreme sensitivity rooted in EPs. To investigate this unique state, we design an underwater acoustic metasurface comprising a beam splitter and a retroreflector on opposite sides. We leverage fluid-solid interaction (FSI) as a powerful mechanism to engineer the non-Hermitian coupling, circumventing the necessity for difficult-to-tune gain or loss for the degeneracy. FSI-induced strong nonlocal elastodynamic coupling concurrently morphs the previously independent spatial subspaces, creating contrasting non-Hermitian behaviors in the respective subspaces, with one encoding the projected CPA EP. We prove that the CPA EP inherits core attributes from both states, manifesting the coexistence of macroscopic operational robustness (from CPA) and microscopic topological hypersensitivity (from EP). We further experimentally demonstrate that the CPA EP, in turn, acts as a knob to modulate the FSI coupling channel, allowing its full activation (for perfect anomalous deflection) or, by leveraging the missing dimension, complete suppression (for total reflection). This synergy between FSI and non-Hermitian degeneracies shows potential for multifunctional hydroacoustic devices.

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Non-Hermitian physics [1–4] has provided a compelling paradigm for wave manipulation, with non-Hermitian singularities, most notably exceptional points (EPs) [5–7], at its heart. EPs manifest as topological degeneracies where both eigenvalues and eigenvectors coalesce, resulting in a defective state space characterized by a “missing dimension” [8]. EPs have unlocked a variety of distinctive wave phenomena, including unidirectional invisibility [9–11], ultrasensitive sensing [12–15], and extremely asymmetric reflection [16–18]. Among the diverse manifestations of EPs, a particular state arises—the coherent perfect absorption at an exceptional point (CPA EP) [19–22], manifesting as a special absorption state driven by coherent excitations. Recent studies have actively explored CPA EPs across various platforms, such as parity-time symmetric acoustic waveguides [22], optical microcavities [20], and coupled resonators [19], demonstrating intriguing capabilities like chiral perfect absorption [19] and reflectionless wave routing [20,22].

Unlike a diabolic point [23], where the eigenvalue splitting under perturbation is linear [24], a system operating at an EP exhibits a fractional-power dependence, rendering the rate of eigenvalue change divergent at the singularity and endowing the system with ultrahigh sensitivity [12–15]. Unlike a conventional EP that can coalesce at an arbitrary value, a CPA EP anchors the degeneracy exactly at the scattering zero, making it a counterintuitive state that can embody an anomalously broadened absorption line shape that dictates strong robustness, which coexists with the hypersensitivity inherently rooted in EPs [12–15]. Notably, both contrasting responses manifest simultaneously under the same perturbation, in contrast to previous systems where robustness and sensitivity coexist through different perturbations [17,25]. Such a “dichotomy” even escalates when considering higher-order singularities, since increasing the order of a CPA further broadens the absorption bandwidth [26] (stronger robustness), whereas the fractional power-law scaling of an EP dictates greater sensitivity [15]. This raises a fundamental question: how can a CPA EP manifest as a single state simultaneously embracing both robustness and sensitivity?

To investigate this, we design an acoustic metasurface by leveraging the projected non-Hermiticity [17], which reveals that non-Hermitian degeneracy can naturally emerge in projected spaces of a globally Hermitian system, bypassing the need for fine-tuning intrinsic gain or loss. However, translating the projective non-Hermitian framework into

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continuous wave media necessitates a physical mechanism to couple independent states. The underwater acoustic environment provides an ideal arena for this, as the dynamic coupling between fluid scalar fields and solid elastic waves induces fluid-solid interaction (FSI) across fully closed structures that would otherwise segregate their opposite sides into decoupled subspaces [27–30]. The FSI in underwater metasurfaces [31–33] excites transverse propagation of elastic waves along the structure, introducing a nonlocal elastodynamic coupling that grants additional degrees of freedom for efficient projective non-Hermitian dynamics.

Building upon this platform, we first show that driven by the FSI-induced nonlocal elastodynamic coupling, the global scattering matrix of the metasurface is rendered irreducible, resulting in the effective scattering blocks projected onto the two local subspaces exhibiting distinct non-Hermitian local behaviors, with one anchored at a projected CPA EP (a symmetric CPA EP featuring balanced coupling [20]). Crucially, we reveal the counterintuitive behavior inherent to this CPA EP, demonstrating the coexistence of macroscopic operational robustness [26] inherited from the CPA, and microscopic topological hypersensitivity rooted in the EP. In turn, we experimentally demonstrate the role of the CPA EP in tuning the FSI coupling channel: enabling on-demand switching between perfect anomalous deflection and total reflection.

We begin by considering a generic passive and lossless acoustic system supporting four scattering ports, denoted as ports 1–4. As schematically illustrated in Fig. 1(a), ports 1 and 2 reside in the upper half-space (constituting subspace U), while ports 3 and 4 belong to the lower half-space (constituting subspace L), separated by a solid barrier. The linear scattering process links the incident states,

partitioned as $\mathbf{a} = [\mathbf{a}_U, \mathbf{a}_L]^T$ (with local states $\mathbf{a}_U = [I_1, I_2]^T$ and $\mathbf{a}_L = [I_3, I_4]^T$), to the scattered states $\mathbf{b} = [\mathbf{b}_U, \mathbf{b}_L]^T$. This process is governed by a 4×4 global scattering matrix $\mathbf{S}$ (such that $\mathbf{b} = \mathbf{S}\mathbf{a}$), which takes the block form

$$\mathbf{S} = \begin{bmatrix} \mathbf{R}_U & \boldsymbol{\kappa}_{UL} \\ \boldsymbol{\kappa}_{LU} & \mathbf{R}_L \end{bmatrix} = \{s_{ij}\}, \quad (1)$$

where the matrix element s_{ij} represents the complex scattering coefficient from port j to port i . The 2×2 submatrices $\mathbf{R}_U$ and $\mathbf{R}_L$ on the main diagonal describe the local scattering (i.e., reflection) behaviors within the upper and lower half-spaces, respectively. The off-diagonal matrices $\boldsymbol{\kappa}_{UL}$ and $\boldsymbol{\kappa}_{LU}$ encapsulate the intersubspace coupling from L to U and from U to L . In the absence of FSI (equivalent to an acoustically rigid barrier), the intersubspace coupling completely vanishes ($\boldsymbol{\kappa}_{LU} = \boldsymbol{\kappa}_{UL} = \mathbf{0}_{2 \times 2}$), and the global scattering matrix $\mathbf{S}$ strictly reduces to a block-diagonal form [Fig. 1(b)], indicating two completely decoupled half-spaces [back panel, Fig. 1(a)]. Since $\mathbf{R}_U$ and $\mathbf{R}_L$ are unitary matrices, they admit a complete orthonormal eigenbasis.

The FSI fundamentally alters this paradigm, serving as a nonlocal coupling bridge between these subspaces [front panel, Fig. 1(a)] and resulting in an irreducible global matrix $\mathbf{S}$ [Fig. 1(b)]. The concept of projected non-Hermiticity [17] allows us to explore non-Hermitian behaviors within local subspaces by considering the projection of the globally unitary scattering process onto a single side. When excitations are exclusively restricted to, for example, subspace U (i.e., the incident state $\mathbf{a}_L = \mathbf{0}$), the scattering operator observed on this side is given by the subblock,

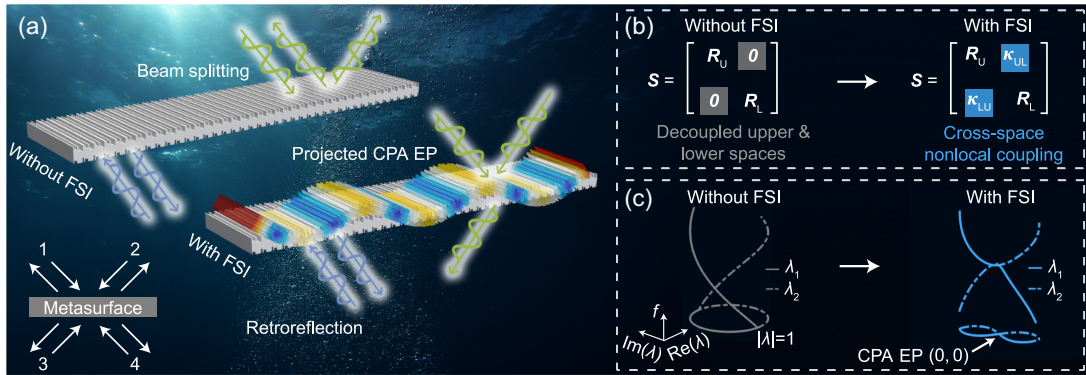


FIG. 1. Conceptual illustration of the projected CPA EP enabled by nonlocal elastodynamic coupling. (a) Without FSI, the metagrating acts as an acoustically rigid barrier, decoupling the upper and lower subspaces (back panel). Incident waves from either side undergo total reflection (blue and green arrows). The activation of FSI bridges the two subspaces via elastodynamic coupling (front panel). Under coherent excitation matching the degenerate eigenstate (green arrows), reflection in the upper subspace is entirely suppressed and routed to a specific port in the lower subspace. Conversely, the single-port incidence from the lower subspace (blue arrows) remains completely immune to the FSI coupling, maintaining perfect retroreflection. (b) Without FSI, the $\mathbf{S}$ matrix is block diagonal with zero off-diagonal blocks, representing the decoupled subspaces. The activation of FSI introduces coupling blocks ($\boldsymbol{\kappa}_{UL}$ and $\boldsymbol{\kappa}_{LU}$), bridging the cross-space wave transmission channels. (c) Without FSI, the eigenvalues λ_1 and λ_2 lie on a unit circle ($|\lambda| = 1$). With FSI coupling, the eigenvalue trajectories evolve and coalesce precisely at the origin $(0, 0)$, demonstrating the projected CPA EP.

$S_U = R_U = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}$. Grounded in the global energy conservation ($S^\dagger S = I$), the analytical property of this projected matrix is governed by the relation $S_U^\dagger S_U = I - \kappa_{LU}^\dagger \kappa_{LU}$, which reveals that the FSI-induced nonzero coupling (κ_{LU}) introduces non-Hermiticity into the respective subspaces.

We present a proof-of-concept to demonstrate that FSI-induced coupling enables the simultaneous synthesis of distinct projected non-Hermitian scattering behaviors within a compact unitary system. Here, within subspace U , the projected matrix S_U encodes a CPA EP state. At this state, eigenvectors of S_U coalesce, accompanied by the degenerated eigenvalue vanishing ($\lambda_{1,2} = 0$), as shown in Fig. 1(c). For our reciprocal two-port subspace (so that $s_{12} = s_{21}$), satisfying this singularity demands analytical constraints on the matrix elements: $s_{11} = -s_{22} = \pm i s_{12}$ [see detailed derivations in Supplemental Material (SM) [34], Sec. A]. Physically, this dictates that under coherent excitation with the degenerate eigenstate, reflections within subspace U are entirely suppressed, and all acoustic energy is 100% “dissipated” from the perspective of subspace U . Unlike standard CPA EP realized through intrinsic loss tuning, non-Hermiticity here exclusively manifests within this lower-dimensional subspace, by exploiting intersubspace coupling as an effective leakage loss. Concurrently, the projected matrix in the complementary subspace L is engineered to manifest a special state featuring a diagonal form, i.e., $|S_L| = |R_L| = \text{diag}(0, 1)$. This state breaks conventional symmetric scattering, allowing the incident energy from subspace U routed 100% to a certain port of the complementary subspace L .

We design a stainless steel groove-type metasurface [Fig. 1(a)] to realize the above functionalities. The periodicity, D , is governed by diffraction kinematics to support exactly two diffraction channels (the zeroth and first orders) under $\pm 45^\circ$ incidence, defining a two-port subsystem on each side. Since the required number of grooves correlates with the number of supported diffraction channels [35], each unit cell features two grooves on each side. Such metasurfaces enable fine-tuning of each S element via groove geometries, facilitating inverse design through full-wave FSI simulations (see SM [34], Sec. B for design details). We first design a reflective boundary, which will later constitute the upper side of the assembled metasurface, to function as a beam splitter ensuring an equal 50/50 energy split among the two reflection channels [green arrows in the back panel of Fig. 1(a)]. Concurrently, the other reflective boundary (constituting the lower side of the metasurface) is tailored to function as a perfect retroreflector [blue arrows in the back panel of Fig. 1(a)].

We incorporate these functionally distinct reflective boundaries as opposite sides of a monolithic metasurface. To investigate how the FSI reshapes the subspace U , we introduce a parameter, $\gamma = E/E_0$, to artificially tune the elastic stiffness of the metasurface, where E and E_0 denote the hypothetical and actual Young’s moduli of the metasurface material, respectively. The evolutionary trajectories of the two eigenvalues of S_U are mapped within a three-dimensional parameter space spanned by $\text{Re}(\lambda)$, $\text{Im}(\lambda)$, and the tuning parameter γ along the vertical axis [Fig. 2(a)]. In the acoustically rigid limit ($\gamma \gg 1$), the eigenvalue

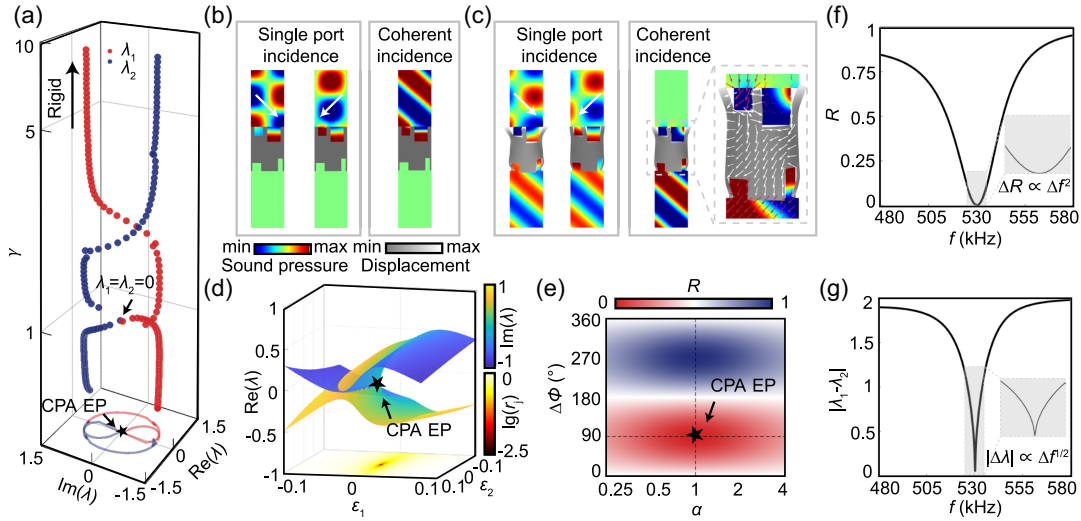


FIG. 2. The FSI-induced CPA EP in subspace U . (a) Trajectories of the scattering matrix eigenvalues $\lambda_{1,2}$ in the complex plane as γ varies. The two eigenvalue branches coalesce at the origin ($\lambda_{1,2} = 0$), identifying the projected CPA EP. (b),(c) Sound pressure and structural displacement distributions for (b) the acoustically rigid ($\gamma \gg 1$) and (c) FSI-dominated ($\gamma = 1$) states. The inset in (c) visualizes the energy transport mechanism, where acoustic intensity (red arrows) and mechanical energy flux (white arrows) bridge the two half-spaces. (d) Riemann sheet of the scattering eigenvalues $\lambda_{1,2}$ in the structural parameter space. The bottom projection of phase rigidity confirms the eigenvector coalescence at the CPA EP (star). (e) Coherent reflectance map versus α and $\Delta\phi$, with the CPA EP (star) located at $\alpha = 1$, $\Delta\phi = 90^\circ$. (f) Coherent reflection spectrum, showing a quadratic profile (inset). (g) Spectral splitting of the eigenvalues, showing a fractional power-law scaling (inset).

trajectories remain independent of γ , and their projection onto the complex plane [the bottom of Fig. 2(a)] forms a unit circle ($|\lambda| = 1$). This geometric signature demonstrates the unitarity of S_U in the absence of FSI-induced coupling. However, as γ decreases, nonlocal FSI is activated, causing the eigenvalue trajectories to intertwine, with their planar projections progressively deviating from the unit circle, manifesting the emergence of projected non-Hermiticity. When $\gamma = 1$, the two trajectories coalesce at the origin of the complex plane. This simultaneous degeneracy and vanishing of the eigenvalues mark the emergence of the projected CPA EP. Practical geometric control of FSI coupling and quantitative characterization of the projected non-Hermitian strength are detailed in SM [34], Secs. C and D.

We perform full-wave simulations incorporating FSI to visualize the scattering field (see simulation details in SM [34], Sec. E). In the acoustically rigid limit ($\gamma \gg 1$), the incident wave undergoes equal-intensity reflection back into both ports under single-port excitation [Fig. 2(b), left panel], while the reflected field can be routed with 100% efficiency into a certain port [Fig. 2(b), right panel] under coherent two-port incidence (see the mathematical relation between the single and coherent incidences in SM [34], Sec. F). In all these rigid-limit scenarios, acoustic energy cannot tunnel through the metasurface, leaving subspace U completely isolated and preserving a unitary S_U . In contrast, the activation of the FSI reshapes the scattering behavior. Under single-port incidence [Fig. 2(c), left and middle panels], the metasurface bisects the incident energy, reflecting 50% into the upper half-space with strong interference and tunneling the remaining 50% through the FSI channel into the lower half-space. The mechanism of FSI is further elucidated in the magnified inset in the right panel of Fig. 2(c). We observe a clear transduction pathway of energy flux: injected into the structure, converted into elastic strain energy, and ultimately reradiated into the transmission channels. Crucially, this dynamic process induces significant elastic deformations, notably the bending of the groove walls and the flexural deformation of the entire metasurface plate, manifesting the transverse propagation of elastic waves along the metasurface. Such elastodynamic energy transport across adjacent unit cells substantiates the nonlocal coupling mechanism [3].

To investigate the topology of the FSI-induced projected CPA EP, we span a two-dimensional geometric parameter space defined by structural perturbations—the relative height variation of the first groove (ε_1) and the relative width variation of the second groove (ε_2) on the upper surface—to the metasurface unit (see details about the perturbations in SM [34], Sec. B). Figure 2(d) maps the complex eigenvalues of S_U onto a three-dimensional Riemann surface, exhibiting a characteristic self-intersecting Riemann sheet structure culminating in a distinct branch point singularity. Notably, this branch point is

anchored precisely on the zero plane of $\text{Re}\{\lambda\} = 0$, confirming the CPA EP. Alongside, the phase rigidity of the eigenvectors [36–38] also drops and approaches zero at the CPA EP, confirming the deficiency of the eigenspace (see discussions of phase rigidity in SM [34], Sec. J). Unlike conventional scattering EPs featuring a Jordan-block form and accessible via single-port excitation [39–42], CPA EPs can only be triggered by coherent excitations. By parametrizing a general dual-port coherent incident state as $\mathbf{v} = (1/\sqrt{1+\alpha^2})[1, \alpha e^{i\Delta\phi}]^T$, we map the reflectance R (i.e., total reflected energy from both upper channels divided by the incident energy) against the input amplitude ratio α and phase difference $\Delta\phi$ [Fig. 2(e)]. This confirms the singular point, showing absolute zero reflection precisely when the excitation matches the degenerate eigenstate $\mathbf{v}_{1,2} = (1/\sqrt{2})[1, i]^T$ (corresponding to $\alpha = 1$, $\Delta\phi = 90^\circ$) in the parameter space (see SM [34], Secs. G and H for detailed discussions). Note that alongside the emergence of the projected CPA EP in subspace U , the induced FSI coupling concomitantly reshapes the lower half-space (see details in SM [34], Sec. I), with further topological signatures of the CPA EP detailed in SM [34], Sec. J.

Importantly, the CPA EP brings us to a unification of sensitivity and robustness within a single degenerate state, under the same perturbation— f . On one hand, the eigenvalue splitting precisely follows a fractional power-law scaling, $\Delta\lambda \propto \Delta f^{1/2}$, which yields a divergent rate of change exactly at the singularity [$(d/df)\Delta\lambda \rightarrow \infty$], manifesting extreme sensitivity. On the other hand, the physically measurable observable, the reflectance R , exhibits a quadratic dependence on the frequency detuning, $R \propto \Delta f^2$ (a symmetric CPA EP featuring balanced coupling [20]), guaranteeing a vanishing derivative at the target frequency [$(d/df)R = 0$] and ensuring robust coherent reflection suppression. Thus, the spectral dynamics of the metasurface in the vicinity of the CPA EP can be investigated from two distinct yet complementary perspectives: the reflection spectrum $R(f)$ exhibits a quadratic line shape [Fig. 2(f)], while the eigenvalue splitting $\Delta\lambda$ of S_U as a function of frequency features a square-root dependence [Fig. 2(g)]. In this way, the degenerate state simultaneously embraces both the microscopic sensitivity intrinsic to the EP and the macroscopic robustness characteristic of CPA. Although these features operate at different scales without direct conflict, their coexistence remains remarkable. Generally, the scattering behavior of a system is governed by its scattering matrix (S), while S is in turn characterized by its eigenspace. Now, the CPA EP induces a split between them: the internal eigenspace infinitely amplifies the perturbation, while the external scattering field completely suppresses it. This is the very consequence of two eigenvalues degenerating to exactly zero, making CPA EPs so different from conventional EPs. In SM [34], Sec. K, we establish the mathematical correspondence between the

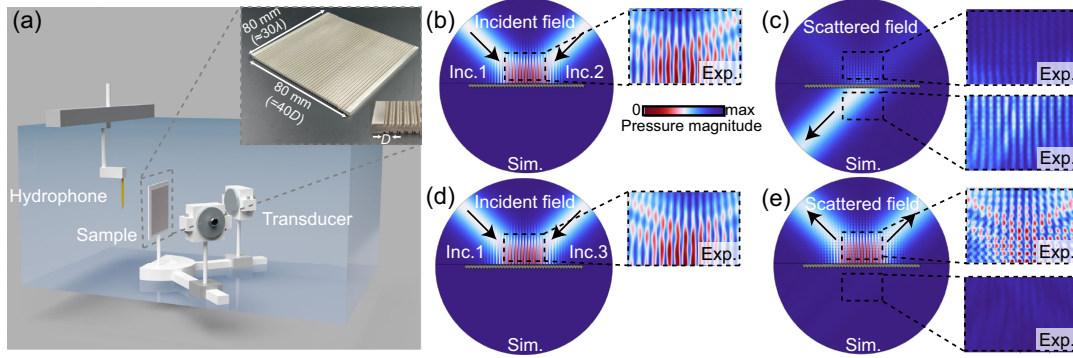


FIG. 3. Experimental observation at the projected CPA EP. (a) Schematic of the underwater acoustic experimental platform and a photograph of the fabricated sample (inset). (b)–(e) Comparison between numerical simulations (left) and experimental measurements (right) of the pressure fields at the projected CPA EP under coherent incidence matching the degenerate eigenstate (b) and (c), and exclusively coupled to the missing dimension (d) and (e). The incident pressure distributions in (b) and (d) correspond to free-field coherent excitation in the absence of the metasurface.

microscopic sensitivity and the macroscopic robustness. Note that the projected CPA EP exhibits the same topological characteristics as a standard one driven by intrinsic loss (see discussions in SM [34], Sec. L).

To experimentally investigate the interplay between FSI coupling channel and the projected CPA EP, we established an underwater acoustic measurement platform [Fig. 3(a)]. The metasurface sample, comprising 40 periodic unit cells, was fabricated from stainless steel and immersed in a large water tank. The excitation setup utilized two underwater transducers (V389-SU, Olympus) positioned symmetrically at 45° relative to the sample normal. We first generated coherent incident beams satisfying exactly the eigenstate $\mathbf{v}_{1,2} = (1/\sqrt{2})[1, i]^T$ (i.e., $\alpha = 1$ and $\Delta\phi = 90^\circ$) after rigorous acoustic calibration (see experiment details in SM [34], Sec. M). On the detection side, a hydrophone (NH1000, Precision Acoustics) integrated with a three-axis computer-controlled positioning system (UMS4, Precision Acoustics) was employed to map the spatial acoustic fields. Figure 3(b) displays the numerical and experimental incident fields, characterized by a dual-beam interference pattern, mapped within a predefined scanning area, where the experimental result was acquired in the absence of the sample. Figure 3(c) presents the corresponding scattered field, covering both the reflection region in the upper half-space and the transmission region in the lower half-space. Under the coherent excitation matching the CPA EP eigenstate, the FSI coupling channel is fully activated, efficiently channeling the acoustic energy flux into the lower half-space and manifesting as a clear, highly directional transmitted beam, accompanied by a fully suppressed reflection.

We then excite the metasurface with an incident field orthogonal to the CPA EP eigenstate, given by $\mathbf{v}_\perp = (1/\sqrt{2})[1, -i]^T$ (i.e., $\alpha = 1$ and $\Delta\phi = -90^\circ$). As depicted in Fig. 3(d), both simulation and experiment reveal an incident dual-beam interference pattern very similar to that

of the eigenstate excitation. However, the resulting scattered field [Fig. 3(e)] exhibits a contrasting behavior (see quantitative comparisons between the measured and simulated results in SM [34], Sec. M). Physically, the coalescence of eigenstates at an EP inherently leaves the Hilbert space incomplete. The missing dimension provides an exotic channel that is fully decoupled from the EP environment [8], causing the FSI coupling channel to be completely hidden. Consequently, acoustic energy is strictly prohibited from penetrating the metasurface, remaining entirely localized within the upper half-space as total reflection. These results demonstrate that the CPA EP enables the FSI coupling channel to be switched between being fully activated and completely suppressed. Note that slight field deviations from the numerical results primarily stem from our time-domain measurements. Comprehensive quantitative comparisons, corresponding transient simulations, and experimental results for lower-surface incidence are provided in SM [34], Sec. M.

To conclude, we have theoretically proposed and experimentally validated an acoustic metasurface anchored at a projected CPA EP, driven by nonlocal elastodynamic FSI coupling. We unveil the uniqueness of the CPA EP as the unification of hypersensitivity and robustness. Although this EP-induced sensitivity is microscopically confined to the internal eigenspace, it holds the potential to be experimentally resolved through the spatial distribution of reflection [17,43], rather than the total energy of reflection. Beyond these, harnessing the CPA EP and its missing dimension to, in turn, modulate the FSI coupling channel shown in this work may provide a versatile paradigm for macroscopic wave control, paving the way for non-Hermitian hydroacoustic devices.

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